1 INTRODUCTION

The high energy electron injection (E-Beam) technology developed by High Voltage Environmental Applications, Inc. (HVEA) was demonstrated by Haley and Aldrich, Inc. for the treatment of groundwater contaminated with methyl *t*-butyl ether (MtBE) at the Naval Base Ventura County (NBVC) in the summer and fall of 2001. This Innovative Technology Evaluation Report (ITER) describes the results of that demonstration and provides other pertinent technical and cost information for potential users of this technology. For additional information about this technology, and the evaluation site, refer to key contacts listed at the end of this section.

1.1 Purpose and Organization of the ITER

Information presented in the ITER is intended to assist decision-makers in evaluating specific technologies for treatment of contaminated media. The ITER represents a critical step in the development and commercialization of a treatment technology. The report discusses the effectiveness and applicability of the technology and analyzes costs associated with its application. The technology's effectiveness is evaluated based on data collected during the demonstration. The applicability of the technology is discussed in terms of waste and site characteristics that could affect technology performance, material handling requirements, technology limitations, and other factors.

The purpose of this ITER is to present information that will assist decision-makers in evaluating the E-Beam technology for application to a particular site cleanup and for the treated water to be considered as a source of drinking water. This report provides background information and introduces the E-Beam technology (Section 1.0), analyzes the technology's applications (Section 2.0), analyzes the economics of using the E-Beam technology to treat contaminated groundwater (Section 3.0), provides an overview and evaluation of the E-Beam demonstration at the NBVC (Section 4.0), summarizes the technology's status (Section 5.0), and presents a list of references used to prepare the ITER (Section 6.0). Vendor's claims for the E-Beam technology are presented in Appendix A.

1.2 Description of the MtBE Demonstration Program

In 1999, the U.S. Environmental Protection Agency (EPA) and the U.S. Navy entered into a memorandum of understanding to conduct a multi-year program involving demonstration and evaluation of several innovative technologies for treatment of MtBE in groundwater. Technology vendors were identified through an open solicitation requesting proposals for processes to treat MtBE. Vendors participating in the program were selected based on the results of external and internal EPA/Navy peer reviews.

The site that was selected for the multiple-vendor MtBE demonstration program was the source zone of the Naval Exchange (NEX) Gasoline Station site, located at the NBVC, Port Hueneme, California. The NEX Gasoline Station site is typical of similar gasoline service station sites throughout the country, where leaking gasoline storage tanks and product delivery lines have contaminated surrounding groundwater with gasoline components and additives, including MtBE. The MtBE plume that emanates from the NEX Gasoline Station at the NBVC site extends approximately 5,000 feet from the contamination source in a shallow perched aquifer (SCS and Landau Associates 1985).

Three locations within the MtBE plume at the NEX Gasoline Station site were identified as potential locations for technology demonstrations. These three locations are differentiated by their distance from the source and are identified as follows:

1. **Source Zone**: This zone is closest to the source, contains high concentrations of MtBE as well as benzene, toluene, ethylbenzene, and xylenes (BTEX), and potentially contains free-phase gasoline.

2. **Middle Zone**: This zone is the area mid-way down gradient along the MtBE plume contains moderate concentrations of MtBE; no BTEX or free-phase gasoline is known to be present.

3. **Wellhead Protection Zone**: This zone is farthest down gradient along the plume, and contains MtBE at lower concentrations than the first two zones.

Figure 1-1 indicates the extent of the MtBE plume at Port Hueneme as of August, 1999 and identifies the three zones within the plume; Figure 1-2 provides an expanded view of the Source Zone, the location of the E-Beam technology demonstration.

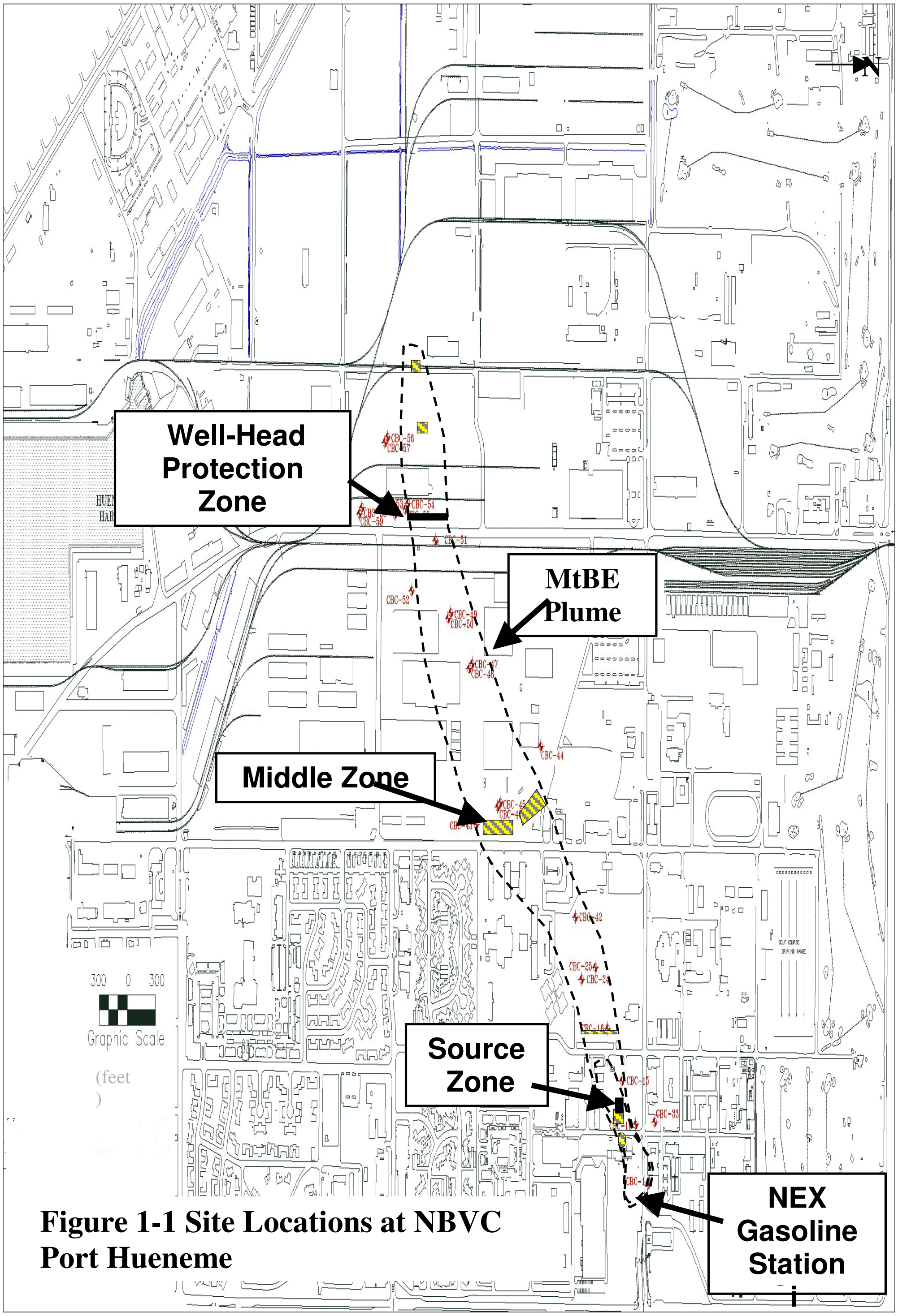

Figure 1-1 Site Locations at NBVC Port Hueneme

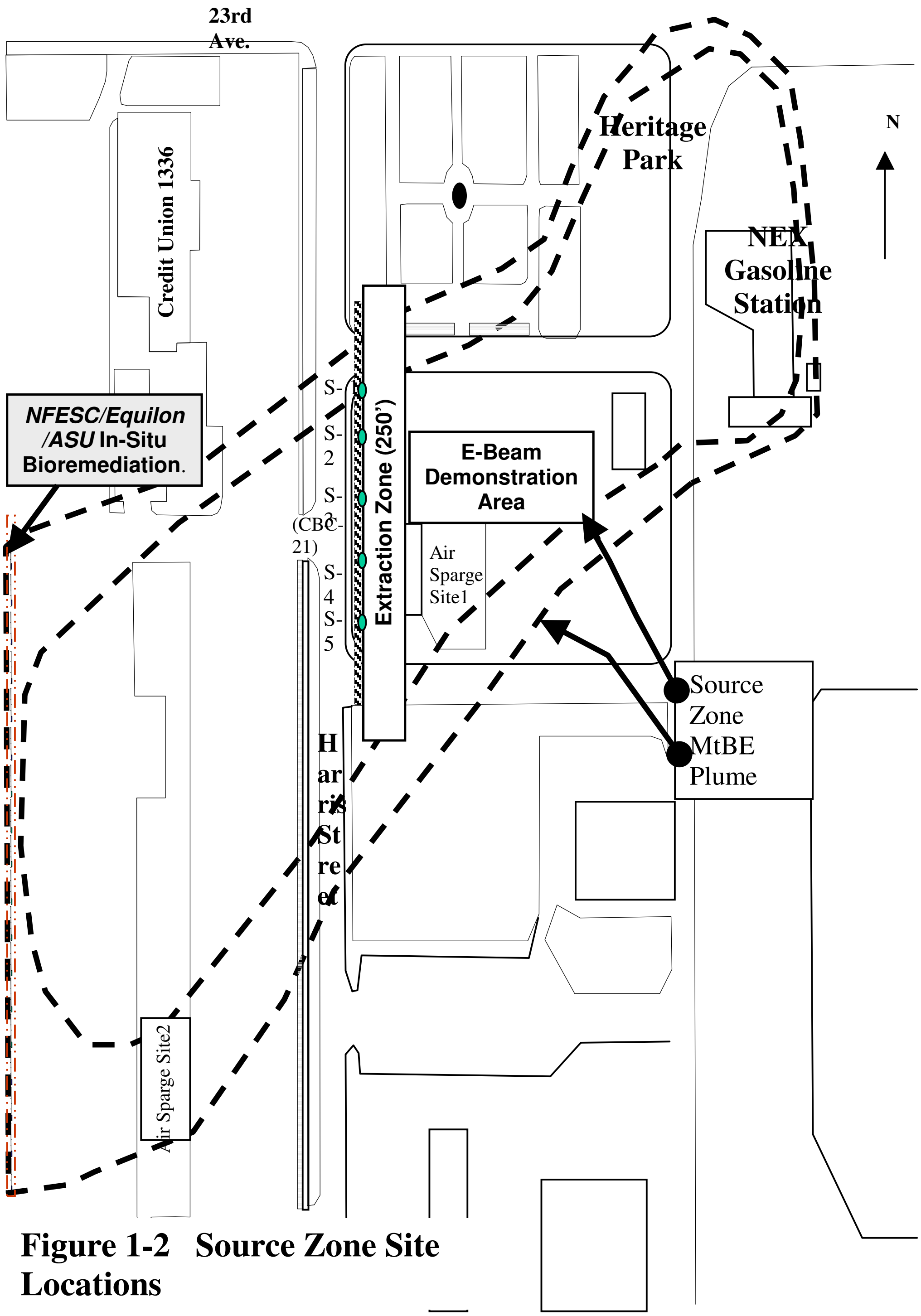

Figure 1-2 Source Zone Site Locations

1.3 Technology Description

This section describes the HVEA E-Beam technology that was operated by Haley and Aldrich, Inc. and demonstrated at the NBVC, Port Hueneme, California.

1.3.1 Principles of the E-Beam Technology

The E-Beam technology destroys organic contaminants in groundwater through irradiation with a beam of high-energy electrons. The injection of accelerated electrons into an aqueous solution results in the formation of reactive species described by equation 1 (Buxton et al., 1988):

$$H_2O \text{ -/\!\backslash\!/\!\backslash\!\backslash } \rightarrow (2.7)\,\dot{}OH, (0.6)\ \dot{H}, (2.6)\ e^-_{aq}, (0.45)\ H_2, (0.7)\ H_2O_2, (2.6)\ H_3O^+ \qquad [1]$$

The numbers in parentheses denote the yield (G-value) of each species per 100 eV absorbed dose (energy). This can be thought of as an efficiency estimate, that is, the relative concentration of a radical, excited species, or molecule per unit-absorbed energy.

During irradiation of water, three primary transient reactive species are formed: aqueous electrons (e^-_{aq}) and hydrogen radicals (•H), which are strong reducing species; and hydroxyl radicals (•OH), which are strong oxidizing species. These reactive species can destroy organic compounds initially present in water at part-per-million (ppm) concentrations, in most cases, to non-detectable concentrations. Because three reactive species are formed, there are multiple mechanisms or chemical pathways for organic compound destruction. In this way, the E-Beam technology differs from other technologies that involve free radical chemistry, which typically rely on a single reactive species in the organic compound destruction mechanism, usually •OH. The entire sequence of reactions between organic compounds and reactive species occurs in the area where the E-Beam impacts the water and is completed in milliseconds. As high-energy electrons impact flowing water, the electrons slow down, lose energy, and react with water to produce the three reactive species responsible for organic compound destruction, as well as hydrogen (H_2), hydrogen peroxide (H_2O_2), and hydronium ions (H_3O^+).

Equation 1 shows that the •OH and e^-_{aq} account for about 90 percent of the three primary reactive species formed by the E-Beam. According to published results and computer models provided by Haley and Aldrich that simulate radiation chemistry in water, some compounds are preferentially destroyed by either •OH or e^-_{aq}. For example, chlorinated hydrocarbons such as chloroform are dechlorinated by a reaction with e^-_{aq} that initiates a series of subsequent reduction and oxidation reactions leading to hydrocarbon mineralization. Other organic compounds undergo a variety of reactions, including addition, hydrogen abstraction, electron transfer, and radical-radical combination. For example, the BTEX compounds are initially destroyed primarily through •OH initiated reactions.

The E-Beam is produced using an electron accelerator. Within the electron accelerator, a stream of electrons is emitted when an electric current (beam current) is passed through a tungsten wire filament. The electron stream is accelerated by applying an electric field and is focused into a beam using collimating plates. The applied voltage determines the energy (speed) of the accelerated electrons, which affects the depth to which the E-Beam penetrates the water being treated. The number of electrons emitted per unit time is proportional to the beam current; therefore, the E-Beam power is the product of the beam current and the accelerating voltage.

Dose is the amount of energy from the E-Beam that is absorbed by the irradiated water per unit mass. Dose is expressed in kilorads (krads); a krad is defined as 10^5 ergs of absorbed energy per gram of material. The dose depends on (1) the density and thickness of the water stream; (2) E-Beam power, which is a function of current and accelerating voltage; and (3) the amount of time the water is exposed to the E-Beam, which depends on the flow rate of the water. Dose is the principal operating parameter that affects the performance of the E-Beam technology.

The E-Beam treatment technology does not generate residue, sludge, or spent media that require further processing, handling, or disposal. Target organic compounds are either mineralized or broken down into lower molecular weight compounds. It has been shown that the E-Beam produces transient~~,~~ reactive species that react with contaminants to produce intermediate chemical species that are ultimately oxidized to carbon dioxide (CO_2), water, and salts. At low to intermediate doses, however, incomplete oxidation may result in the formation of unwanted chemical by-products such as low molecular weight aldehydes, organic acids, and semi-volatile organic compounds (SVOC). A number of reports have recently been published that detail this chemistry (Cooper et al., 2000; 2001;Hardison et al., 2002; Kim et al., 2002; Mezyk et al., 2001; O'Shea et al., 2001; 2002; Tornatore et al., 2000; Wu et al., 2002).

Haley and Aldrich notes that these by-products may include formaldehyde, acetaldehyde, glyoxal, and formic acid. In a recent demonstration of the technology in application to groundwater contaminated with trichloroethene (TCE) and tetrachloroethene (PCE), the vendor claims that aldehydes were formed at concentrations that accounted for less than 1 percent of the total organic carbon (TOC) content (Cooper et al., 1993). The vendor claims that at low doses (50 krads), formic acid accounted for up to 10 percent of the TOC content; however, this percentage decreased at higher doses (greater than 200 krads). According to the vendor, chloride ion (Cl^-) mass balances indicated that complete conversion of organic chlorine to Cl^- occurred during treatment. Additional research indicates that haloacetic acids, such as chloroacetic acid, may be formed (Gehringer et al., 1988).

1.3.2 Description of E-Beam Process

A diagram of the E-beam system that was used for the demonstration is shown in Figure 1-3. The E-beam system is housed in an 8-foot by 48-foot trailer and is rated for a maximum flow rate of 40 gallons per minute (gpm). The E-beam system is composed of the following components: a strainer basket, an influent pump, the E-beam unit, a cooling air processor, a blower, and a control console (not shown in Figure 1-3). These components are situated in three separate rooms: the pump room, process room, and control room. The pump room contains all ancillary equipment for both water and air handling; the radiation-shielded process room contains the E-beam unit itself; and the control room contains the control console where system-operating conditions are monitored and adjusted.

For the demonstration, the influent pump transferred contaminated groundwater from the five wells in the groundwater extraction zone to the E-beam unit. A strainer basket located upstream from the influent pump removed particulate matter greater than 0.045 inch in size from the groundwater to prevent damage to the influent pump and other components of the treatment system.

The E-beam unit is composed of the following components: an electron accelerator, a scanner, a contact chamber, and lead shielding. The electron accelerator used for the demonstration is capable of generating an accelerating voltage of 500 kilovolts (kV) and a beam current of between 0 and 42 milliamps (mA). The accelerating voltage determines the E-beam penetration depth. Based on the maximum accelerating voltage and beam current that the electron accelerator can generate, the E-beam unit has a maximum power rating of 21 kW.

A scanner located beneath the electron accelerator uses magnetic coils to deflect the E-beam, causing it to scan into a prescribed shape and penetrate the flowing water (the E-beam scanner operation is similar to the vacuum tube in a television set). Contaminated groundwater is pumped through the contact chamber, which is located beneath the scanner. The scanner is operated in such a way that the E-beam contacts the entire surface of the water flowing through the contact chamber.

Two titanium membranes/windows separate the scanner from the contact chamber. The first (primary) window maintains a vacuum in the scanner and the second (secondary) titanium window isolates cooling air from the contact chamber; as the E-beam passes through the primary titanium window, a small amount of the E-beam's energy is absorbed by the window. This energy absorption is manifested in the form of heat. Because of the E-beam's high energy and operation in a confined space, at high power the titanium window may experience undesired heating. Passing recirculating cooling air between the primary and secondary windows cools the titanium window. Cooling air exiting from between the two windows flows through a cooling air processor, which includes a water-jacketed air chiller, and is then returned to re-cool the primary window by a blower.

Ozone, which is formed in the closed loop cooling air when it is exposed to the E-beam, is destroyed by the high discharge temperature (around 300° F) of the blower, according to Haley and Aldrich. Ozone is present in the cooling air return lines, which operate under a slight vacuum, until passing through the blower. However, the ozone concentration in the cooling air return lines is not routinely monitored because the cooling air system is a "closed loop" system, and ultimately the ozone is destroyed as the cooling air is heated by the blower.

Incidental leakage from the cooling system or atmospheric air present in the confined delivery system tends to create a buildup of ozone in the air space under the lead shielding. A vent system and associated ozone destruction unit (not shown in Figure 1-3) was installed to vent this ozone buildup, destroy it, and exhaust the heated air from the trailer. When the E-beam system is operating, both the influent pump and the blower run continuously. If either water or cooling airflow stops, the system automatically shuts down. Lead shielding surrounds the E-beam unit to prevent incidental X-ray emissions. X-rays are formed when the E-beam contacts various internal stainless steel surfaces. As an added safety measure, the process room is inaccessible and interlocked to shut down in the event of entry during system operation.

Resistance temperature devices (RTD) are used to measure the temperature of groundwater before and after treatment. The change in water temperature induced by application of the E-Beam is the method to determine the E-beam dose. The water temperature is expected to increase by about 1°C to 3°C during treatment, depending on the E-Beam dose. The RTDs have a sensitivity of 0.1°C. A relationship between dose and beam current has been established, and the beam current is used for operational control of the system.

The contaminated groundwater flow rate is adjusted in the pump room, using the system's positive displacement influent pump and variable speed drive and is measured by a flow meter. The rotameter-type flow meter installed in the trailer has a 0 to 20 gpm working range. The cooling-air flow rate was determined by the manufacturer of the electron accelerator. Operationally, it is monitored by measuring the pressure drop across the contact chamber. The pressure drop is displayed on the control panel.

Influent and effluent water sampling ports are installed in the trailer-mounted E-Beam system for purposes of sampling untreated and treated water, as shown in Figure 1-3. The 500-gallon influent storage tank was not used during the demonstration except for start-up operations and to check the flow meter for accuracy.

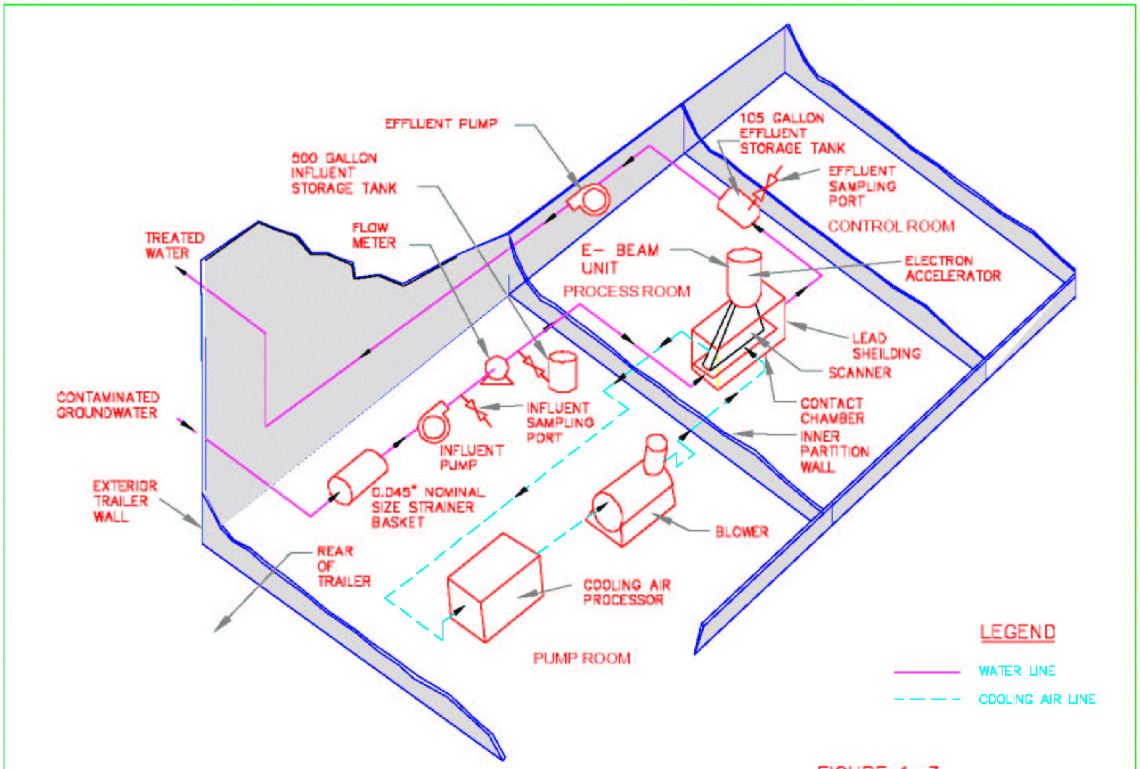

FIGURE 1-3
E-BEAM TREATMENT SYSTEM SCHEMATIC

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